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Applicability of geotechnical approaches and constitutive models for foundation analysis of marine renewable energy arrays

Jason E. Heath[a,*], Richard P. Jensen[a], Sam D. Weller[b], Jon Hardwick[b], Jesse D. Roberts[c], Lars Johanning[b]

[a] *Department of Geomechanics, Sandia National Laboratories, PO Box 5800, Mail Stop 0750, Albuquerque, NM 87185-0750, USA*
[b] *Renewable Energy Group, SERSF Building, College of Engineering, Mathematics and Physical Sciences, University of Exeter, Penryn Campus, Cornwall TR10 9FE, United Kingdom*
[c] *Department of Water Power Technologies, Sandia National Laboratories, PO Box 5800, Mail Stop 1124, Albuquerque, NM 87185-1124, USA*

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ABSTRACT

For Marine Renewable Energy (MRE) to become a viable alternative energy source, it must encompass large arrays of devices. Arrays may include 1000s of devices. The associated foundations or anchors may encounter a range of seafloor sediment types and geotechnical properties. Wave and tidal energy convertors induce unique loads on foundations and anchors that are different from other seafloor engineering applications. Thus, there is a need for a combination of advanced site analysis and performance assessment. Geotechnical engineering plays the vital role of ensuring that foundation and anchor systems perform successfully for MRE devices. Our paper reviews the unique frequency and magnitude of loading regimes experienced by MRE arrays. We examine potential loading conditions on the foundation-anchor systems. Loading regimes include environmental and system loads from single devices or arrays of devices. We present specific load examples from field data. We explore the applicable geotechnical approaches to address these conditions, including constitutive models that may or may not adequately capture the response of the seafloor sediments to the MRE loads. Partially to fully dynamic constitutive model formulations may be necessary to properly model sediment-fluid hydromechanical response to MRE loading. Spacing of full MRE arrays and spatial variability in sediment properties may require multiple foundation types.

1. Introduction

Commercial-scale marine renewable energy (MRE) systems will involve arrays of devices that secure to the seafloor via foundations or anchors. In order to achieve global installed capacity targets (e.g., 10–20 GW by 2050 in the UK [1]), device arrays are likely to occupy areas up to several square kilometers [2–4] that may span across multiple seafloor environments [5]. These devices will transmit loads to the seafloor sediment, soil, or rock—hereafter referred to as “geomaterials”—which may affect seafloor geomaterial properties and the overall physical performance of an MRE system. Multiple devices may be tethered to a single anchor, thereby creating fully three-dimensional dynamic loading scenarios [4]. Cyclic or periodic loading may induce degradation in stiffness and strength of geomaterials, which may cause potential creep movement of foundations or anchors [6–8]. Liquefaction is also possible under high frequency rapid loading and vibration, especially of cohesionless geomaterials [8].

Experience with fully-deployed commercial-scale arrays of tidal- or wave-energy convertors is limited—to date, small-scale arrays and single such devices have been tested [9–12]. Recent MRE-specific research on arrays focuses on hydrodynamics of tidal and wave MRE systems [2,3,13,14]. Foundation, anchor, and geomaterial response for MRE arrays have received less attention, mainly for offshore wind turbine arrays [15]. Thus, the response and performance of seafloor geomaterials is uncertain, given the combination of potentially large MRE arrays, seafloor heterogeneity, unique loading profiles of tidal and wave energy convertors, and coupled hydromechanical-seafloor behavior. As foundations and anchors represent a primary cost to construction, maintenance, and performance of MRE systems [16,17], success of this new industry depends on accurately predicting and designing the response of seafloor geomaterials.

A major research gap is lack of knowledge on the applicability of currently-available geomaterial constitutive models for the unique loading magnitudes, frequencies, and scenarios of MRE wave and tidal energy convertor arrays. Geotechnical approaches and constitutive models were not originally developed for the unique MRE scenarios,

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[*] Corresponding author.
E-mail address: jeheath@sandia.gov (J.E. Heath).

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and thus should be assessed for their applicability. To address this gap, this paper reviews the offshore structure and MRE-related literature, augmented with novel loading information from deployed MRE systems (see Section 2). The objective is to generate knowledge on what geotechnical approaches and constitutive models are available, suited, and preferable for capturing the seafloor geomaterial heterogeneity and response under MRE loading conditions (see Section 3). The paper discusses what future work is needed—including laboratory, field, or numerical modeling—to evaluate or develop appropriate geotechnical approaches and constitutive models if they do not currently exist (see Sections 3 and 4). Geologic heterogeneity is also addressed in the context of variability of seafloor geomaterial properties and the potential size of MRE arrays, which in turn may affect the uniformity, robustness, or mix of different foundation-anchors systems or MRE devices that may be needed for a single site.

2. Frequency and magnitudes of MRE-induced loads

The magnitudes, frequencies, and number of loading cycles experienced by MRE foundations and anchors are specific to both the operational requirements of the device, the type of mooring, anchoring, or foundation system employed, as well as the site location. Loads can be broadly classified as follows: static loading (e.g., due to mooring line pretension); long-term cyclic loading (e.g., during operational and storm conditions); and impulse loading. Seismic loading, a form of impulse loading, may also be important in areas prone to earthquakes. These types of loading all fall under different assumptions for modeling stress-strain and geomaterial response, including the coupled hydro-mechanical processes owing to the fluid that fills the pores of the porous geomaterials and the type of loading, which will be addressed in detail in Sections 3 and 4. For simplicity, in Section 2 we organize information on environmental loads, systems loads, and load characteristics of arrays of MRE systems, which may manifest the aforementioned static, cyclic, and impulse loading to varying degrees (Table 1).

2.1. Environmental loads

Most loads that are applied directly to the MRE structure or device originate from the combined effects of wind, waves, and current [18,19]. These three load sources are rarely co-linear in direction at any one time. For floating devices or sea surface-piercing structures the orbital motion of waves imparts loads at first-order (e.g., typically 5–20 s), second-order, and higher-order frequencies. The magnitude and frequency of wave loading is dependent on a multitude of factors including incident wave characteristics (e.g., significant height, peak period, spectral shape, and directionality), device size, water depth, and bathymetry [2,20]. Research has shown that second-order wave loads (which are associated with steady mean drift loads and cyclic drift motions at sum and difference frequencies) should be considered for floating wind turbines [21], and these loads will also be important for MRE devices [22]. The decay of wave particle velocities with depth (d) means that seabed-mounted devices are less susceptible to wave loading in deep water (i.e., $d/L > 0.5$, where L is wavelength [23]). Devices located in shallow water are affected by refraction and shoaling, where horizontal wave loads increase as progressive waves become steeper in profile. It is possible that breaking or slamming waves can lead to impulse (short duration and large magnitude) loads on floating devices and surface piercing structures. Wilkinson et al. in [24] reported experimental model tests of a bottom-mounted hinge type wave energy converter. When comparing the responses of solid and modular type flap structures, it was noted that while the measured surge-load time-series were similar, significant differences occurred in loading of the foundation in the yaw and roll directions (reductions of 43% and 28%, respectively, for the modular structure). For wind turbine monopiles, it has been demonstrated that breaking waves lead to an amplification of the foundation overturning moment [4,25].

Many coastal locations experience multiple tides during each 24 h period. The change in surface elevation will alter the mooring line pretension of floating devices and for fixed structures also change the distribution of applied wave and current loads. In each case this is likely to (albeit temporarily) alter the response harmonics of the floating device structure. The lay-down and uplift of the mooring lines of catenary mooring systems from the seafloor will also be affected by the change in device position. During the tidal cycle the current velocity varies from zero (slack tide) to peak (ebb or flood depending on the direction), with the highest velocities usually measured at the surface. In extreme cases, vortex-induced vibration can cause high frequency loading to support structures and scouring [26] in addition to mooring lines or umbilical cables [20]. Complex loading may also occur in turbulent flows [13].

For surface piercing structures or floating devices, wind also creates another load component of varying magnitude (e.g., wind gusts) and direction that is dependent on the size and shape of the exposed device. Devices that have large areas exposed to the wind will clearly sustain considerable loads in high wind velocities, which will be transferred to the foundation (i.e., mudline bending moment, [27]), or in the case of a floating device, mooring lines and anchors. Even in steady wind conditions the lever arm caused by wind loading of the rotor could cause platform rotations [28] leading to unequal loading of the anchoring points. Intermittent impact from ice flows or marine life and the effects of biofouling may also need to be considered if relevant to the site [29,30]. Combinations of extreme conditions are typically used to ensure that a design is sufficiently robust and detailed dynamic analysis is typically carried out (e.g., [68]). While preliminary guidelines for MRE devices have been developed (e.g., [31]), many refer back to existing offshore certification guidance. For example, DNV-OS-E301 states 100-year return periods for wind and waves with 10-year return period for current for Norwegian and UK sectors [30]. In addition a 50-year return period for water level may also be used [32]. Maintaining anchor or foundation integrity during storm conditions is particularly important as highly variable cyclic loading will occur.

Table 1
Categorized loading sources that may be experienced by MRE device mooring and foundation systems.

Loading type	Example load sources	
Static	Mooring line pretension Steady wind	Steady current Mean wave drift
Cyclic	Wave loading (first-, second- and higher-order) Tidal cycles	Tidal turbulence Power take-off harmonics
Impulse	Wave slamming or breaking Wind gusts Seismic disturbances	Ice flows Marine life Snatch loading

2.2. System loads

In addition to environmental loads applied directly to the device, the mooring system, foundation, or anchor loads are also dependent on the motions of the device and/or power take-off (PTO) system. Snatch loading occurs when slack lines are rapidly loaded as a result of dynamic device motions (e.g., as a steep wave passes [33]). Wave energy converters (WECs) are designed to harness the predominant wave characteristics through passive or active tuning. The response of the device may therefore be close to resonant in one or more modes of motion and, in extreme cases, large motions may lead to significant slamming forces on the structure [34] and the subsequent amplification of loads transmitted to the anchors through the mooring system.